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SEARCH FOR CONJUNCTIVELY DEFIN
TARGET CAN BE SELECTIVELY LIMIT
TO A COLOR-DEFINED SUBSET OF
ELEMENTS

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SEARCH FOR CONJUNCTIVELY DEFINED TARGET CAN BE SELECTIVELY LIMITED TO A COLOR-DEFINED SUBSET OF ELEMENTS

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TNO Defence Research consists of:

CONTENTS | Page

Report No.:	IZF 1993 B-12
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SUMMARY

When searching for a conjunctively defined target, response latencies usually increase with the number of distractor elements, suggesting serial, self-terminating search through all display elements. However, Egeth, Virzi and Garbart (1984) showed that subjects do not necessarily search all display elements, but can limit their search to a color-defined subset of the elements. The present experiments tested Egeth et al.'s conclusions using an improved paradigm. Subjects searched for a target defined as a conjunction of a color and an orientation. RTs for target present trials increased with the number of elements in that color and were independent of the number of elements in the other color, a finding which replicates Egeth et al.'s results. Experiment 1 showed also that selective search of a color-defined subset did not depend on the saliency of the subset. Experiment 2 showed that selective search can be purely color-based and does not depend on luminance or brightness of the subset. Experiment 3 showed that subjects can flexibly change the subset they are searching for trial by trial. Implications of the present findings for current theories of visual search are discussed.

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Visueel zoeken naar een conjunctie-target wordt tot elementen in de kleur van de target beperkt

J. Theeuwes, N.A. Kaptein en A.H.C. van der Heijden

SAMENVATTING

Bij conjunctie-zoeken neemt de reactietijd toe met het aantal elementen dat wordt aangeboden, hetgeen een indicatie is voor een serieel zoekproces onder alle elementen, dat wordt beëindigd zodra de target is gevonden. Egeth, Virzi en Garbart (1984) vonden echter dat niet altijd alle elementen hoeven worden afgezocht, maar dat proefpersonen het zoeken kunnen beperken tot elementen met dezelfde kleur als de target. De in dit rapport beschreven experimenten zijn bedoeld om Egeth e.a.'s conclusies te toetsen met behulp van een verbeterd paradigma. Proefpersonen zochten naar een target die is gedefinieerd als een conjunctie van kleur en oriëntatie. De reactietijden, als de target aanwezig is, nemen toe met het aantal elementen in de kleur van de target, en zijn onafhankelijk van het aantal elementen in de andere kleur. Dit resultaat repliceert de vindingen van Egeth e.a. Experiment 1 toonde verder aan, dat selectief zoeken onder elementen in de target-kleur niet afhankelijk is van de opvallendheid van deze elementen. Experiment 2 toonde aan dat selectief zoeken zuiver op kleurverschil gebaseerd kan zijn, en niet afhangt van luminantie- of helderheidsverschillen. Experiment 3 toonde aan dat proefpersonen de groep elementen die moet worden afgezocht flexibel per aanbieding kunnen variëren. Implicaties van de verkregen resultaten voor recente theorieën voor visueel zoeken worden besproken.

1 INTRODUCTION

In a typical visual search experiment subjects have to search through a number of elements for a prespecified target. In visual search theory a fundamental distinction is made between feature search and conjunction search (Treisman & Gelade, 1980). In feature search the target is unique within one dimension. For instance, the target is a red item among green ones, or a vertical bar among horizontal bars. In conjunction search the target is also unique, but not within one single dimension. Information from two or more dimensions is needed to detect the target. For instance, the target may be a red horizontal bar among red vertical and green horizontal bars, or a small H among large Hs and small As.

Reaction Times (RTs) in feature search are independent of the number of distractor elements, as long as target and distractors are easily discriminable, whereas in conjunction search RTs increase with the number of distractor elements (e.g., Treisman & Gelade, 1980; Treisman, 1988; Duncan & Humphreys, 1989; Carter, 1982; for exceptions see for instance Nakayama & Silverman, 1986; Dehaene, 1989; Enns, 1990; Treisman & Sato, 1990). These findings give rise to the idea that feature search occurs in parallel across the visual field, whereas in conjunction search elements are searched one by one until the target is found. Often this dichotomy is interpreted in terms of a two-stage model of visual processing as introduced by Broadbent (1958; see also Neisser, 1967). According to the two-stage line of reasoning, an early, pre-attentive stage of processing operates without capacity limitations and in parallel across the entire visual field, followed by a later, attentive limited-capacity stage, in which only one element can be dealt with at a time (see, e.g., Treisman & Gelade, 1980; Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Theeuwes, 1993). Using the language of the two-stage model, it is then suggested that features can be detected in the preattentive stage, while attention must be focused serially on *each* element in turn to verify how the features are conjoined (Treisman, 1988; Treisman & Gelade, 1980).

However, some evidence suggests that subjects, when searching for conjunctively defined targets, are able to limit their search selectively to a subset of the presented elements (Egeth, Virzi & Garbart, 1984; Zohary & Hochstein, 1989; Poisson & Wilkinson, 1992). In the experiments of Egeth et al. (1984), subjects searched for a red O in a field of black Os and red Ns (see also Treisman, Sykes & Gelade, 1977). Egeth et al. (1984) varied the number of distractors of one type (e.g. black Os) while keeping the number of distractors of the other type (red Ns) constant. Subjects were told in advance to search for the target through the subset of items that remained constant in number (red items). Egeth et al. (1984) found that search times were independent of the number of out-of-subset distractors (black Os). On the other hand, in a second experiment, search latencies increased with the number of elements as the number of within-subset distractors increased.

These results have been interpreted as evidence for some kind of "guided search", that is, as evidence for the point of view that subjects can selectively limit their search to only those elements that are likely to be the target (e.g., Egeth et al., 1984; Wolfe, Cave & Franzel, 1989; Zohary & Hochstein, 1989). Support for the notion of subset-selective search may be derived from the findings of Carter (1982). In his experiments a target was present on all trials. The stimulus field consisted of a variable number of three-digit numbers. The color of the target and its first two digits were prespecified. Subjects were to name the third digit as fast as possible. Carter (1982) found that, when the colors where sufficiently different from each other, response latencies increased with the number of elements in the target color, and not with the number of elements in the distractor color. Although Carter's paradigm was quite different from that of Egeth et al. (1984), the results suggest that subjects can search selectively through the elements in the target color.

However, it has been argued that one can also account for Egeth et al.'s (1984) results without claiming selective search among a color-defined subset of elements (see Theeuwes, 1993, p.118; see also Cave & Wolfe, 1990; Treisman & Sato, 1990). In Egeth et al.'s experiments the red elements were always more salient than the black ones. The red elements were more salient because they were more luminant than the black ones. In addition, either the number of red and black items was approximately the same (with an array size of five elements), or there were more black elements than red ones. Under the assumption that an element is more salient to the extent that it is more different from the other elements in the stimulus field, red elements on the average were also more salient because of their number (see, e.g., Cave & Wolfe, 1990, pp.249-50). In the design of Egeth et al. the most salient elements are the elements in the target color. Therefore, exactly the same results would have been predicted, if it is assumed that attention is always switched to the most salient elements.

Such a saliency-determined search may also have occurred in the experiments of Poisson and Wilkinson (1992), who investigated the influence of the relative frequency of elements of two distractor types. They found that the target search was fastest for extreme distractor ratios, and relatively slow for displays in which there was an equal number of elements of each distractor type. Similar results have been obtained by Zohary & Hochstein (1989), although they confounded target present and target absent trials. These results support the idea that, at least without specific instructions, the most salient items are searched first, which is in line with the Theeuwes' (1993) interpretation of the results of Egeth et al. (1984).

One goal of the present study is to determine whether it is possible to search selectively through the elements of the target color when salience can not be the factor of importance. In the first experiment the issue of subset-based versus salience-based segregation is addressed by replicating the experiment of Egeth et al. (1984) without confounding target color and salience. In this experiment red and green were used as stimulus colors. Salience differences resulting from the relative number of red and green elements are systematically varied. Also, in Experiment 1 the green elements are more luminant than the red ones, so that the red elements are on the average not more salient than the green ones, and search among the most salient elements does not mimic subset-selective search. If Egeth et al.'s results can be replicated it is demonstrated that their results need not be explained in terms of saliency of searched-for elements. If the attempt to replicate their findings fails under the present conditions, the salience of elements may be of importance, and deserves further investigation.

Except for the changes in paradigm to control for the confound of color and salience, there are other differences in design and stimuli between the present experiments and the experiments of Egeth et al. (1984).

Egeth et al. (1984) investigated color × letter conjunction search. The use of letter stimuli as target and distractors complicates the interpretation of results. Letters themselves are conjunctions of features (see, e.g., Duncan & Humphreys, 1989; Duncan, 1987; Treisman & Gelade, 1980). The type of search involved then depends on the exact choice of target and distractor letters. When the target letter contains a feature that is unique in the stimulus display, search mimics feature search, and otherwise it mimics conjunction search. For instance, search for an O among Ns and Ts *mimics* feature search (Treisman & Gelade, 1980), whereas search for a T among Ls gives results that are typical for conjunction search (Julesz & Bergen, 1983; Wolfe, Cave & Franzel, 1989; Cave & Wolfe, 1990). It is difficult to generalize results obtained with letter stimuli to other search tasks, because these results are explained in terms of the constituents of the letter stimuli.

In the present experiments the target was defined as a color × orientation conjunction. The stimulus field consisted of red and green vertical or tilted line segments. Subjects had to search for a vertical line segment of a prespecified color.

Using the color and orientation dimensions to define target and distractors is not an arbitrary choice. Both the color and the orientation of stimuli can be clearly described and easily manipulated. Search for a target that differs only in color from distractor elements can be selectively made easier or more difficult by varying the degree of color difference between target and distractors (see, e.g., Carter, 1982; Nagy, Sanchez & Hughes, 1990). Also, search for a target that differs only in orientation from its distractors (e.g., Sagi & Julesz, 1985, 1987; Treisman & Gormican, 1988; Moraglia, 1989; Wolfe, Friedman-Hill, Stewart & O'Connell, 1992), can be selectively made easier or more difficult by varying the difference in orientation between target and distractors (see, e.g., Moraglia, 1989, experiment 2; Palmer, Ames & Lindsay, 1993; Wolfe et al., 1992).

For the experiments reported in this study, the fact that color and orientation can be easily manipulated is of great importance. Egeth et al. (1984) also had subjects search selectively for a red O among all O's (i.e. among all letters that differ only in color from the target). Their findings indicated, that subjects can also selectively search among a group of elements of a specific shape, albeit less efficient than among elements of a specific color. (This finding is consistent with the dominance of color differences over form differences in some circumstances; see, e.g., Theeuwes, 1991, 1992; Callaghan, 1989). In the present experiments two search modes are available as well. Subjects are instructed to search among elements of a target color, but possibly could also limit their search to items of a particular orientation. Depending on the choice of color and orientation differences, stimuli might be equally effectively segregated on their orientation as on their color. If the search mode differs from subject to subject, or from trial to trial, mean RTs increase both with the number of green and with the number of red elements, even when on every trial a subset of elements is searched selectively. So, because color differences are not *a priori* dominant over orientation differences (Callaghan, 1989; Theeuwes, 1992), search among elements of the target's orientation has to be prevented by making orientation-based figure-ground segregation difficult.

Palmer et al. (1993; see also Moraglia, 1989) showed that, when searching for an orientation-defined target, search difficulty increases when distractor and target orientations are more alike (see Pashler, 1988, for a similar result with letter stimuli). In order to discourage selective search among items of the target orientation, in the present experiments the difference in orientation between elements was only 20°.

Three experiments are performed to investigate to what extent subjects are capable of selectively limiting search to a subset of elements on the basis of color. In Experiment 1 it is investigated whether the findings of Egeth et al. (1984) can be replicated, while color and salience are disconfounded. In Experiment 2 it is tested whether selectivity is based on color proper, or whether luminance or brightness differences are necessary. In Experiment 3 the flexibility of selective search is assessed.

2 EXPERIMENT 1

The first experiment was an attempt to replicate the findings of Egeth et al. (1984), with an adjusted paradigm. Elements were vertical or tilted line segments instead of letters. Instead of red and black the stimuli were red and green. The elements were presented equispaced on an imaginary circle around the fixation point instead of on positions of a matrix (as in Egeth et al., 1984). Contrary to Egeth et al., in the present experiment the exposure duration was held short enough to prevent directed refixations during stimulus presentation. The number of red elements in the displays varied from trial to trial, instead of a within-block constant number of red elements, as in Egeth et al. (1984).

Two additional modifications were necessary to disconfound salience and target color. In the present experiment, the luminance of the green elements was approximately twice the luminance of the red ones. Finally, the numbers of red and green elements varied independently and unpredictably. Red elements are not more salient than the green ones, neither through luminance, nor through relative number.

Subjects were presented with dim red or bright green line segments. They had to detect as fast as possible whether a red vertical line segment was present or not among a variable number of red tilted and green vertical elements. Subjects were instructed to search only among the red elements, and were informed that this strategy would be effective.

If search can be selectively limited to a color-defined subset of the elements, irrespective of salience, it is expected that search latencies for target present trials are independent of the number of bright green items, and increase with the number of dim red items.

On the other hand, if Egeth et al.'s (1984) results reflect search for the most salient items then it is expected that search latencies for target present trials increase both with the number of green elements and with the number of red elements.

2.1 Method

Subjects

Eight right-handed subjects, ranging in age from 19 to 32 years, participated as paid volunteers.

Apparatus

A SX-386 personal computer (G2) with a NEC Multisync 3D VGA color screen (resolution 640 $\times$ 350) controlled the stimulus presentations and the timing of the events and recorded RTs through Micro Experimental Laboratory software (Schneider, 1988). The '/'-key and the 'z'-key of the computer keyboard were used as response buttons. Subjects were tested in a sound attenuated, dimly lit room with their heads resting on a chinrest adjusted to a comfortable height. The CRT was located at eye level, 97 cm from the chinrest.

Task

Subjects were instructed to determine as quickly as possible, though without making too many errors, whether a red vertical bar (the target) was present in the stimulus field. Half of the subjects had to respond 'target present' by pressing the 'z'-key and 'target absent' by pressing the '/'-key, and half of the subjects responded 'target present' by pressing the '/'-key and 'target absent' by pressing the 'z'-key.

Stimuli

Fig. 1 shows examples of stimulus displays, both with (left) and without a target (right). In target-absent trials the stimulus field consisted of a fixation dot (0.3°), 1, 2, 4 or 6 red 0.6° line segments, tilted 20° clockwise and 1, 2, 4 or 6 green vertical 0.6° line segments. In target-present trials one of the red tilted line segments was replaced by a red vertical line segment: the target. In all trials elements were randomly distributed among equally spaced locations on an imaginary circle with a radius of 3.0° of visual angle. As a consequence, the line segments were separated at least 1.5° of visual angle, which is sufficient to prevent lateral masking effects (see, e.g, Cohen & Ivry, 1989; 1991). All line segments were presented at the same distance from the fixation point, to control for differential retinal processing capacities.

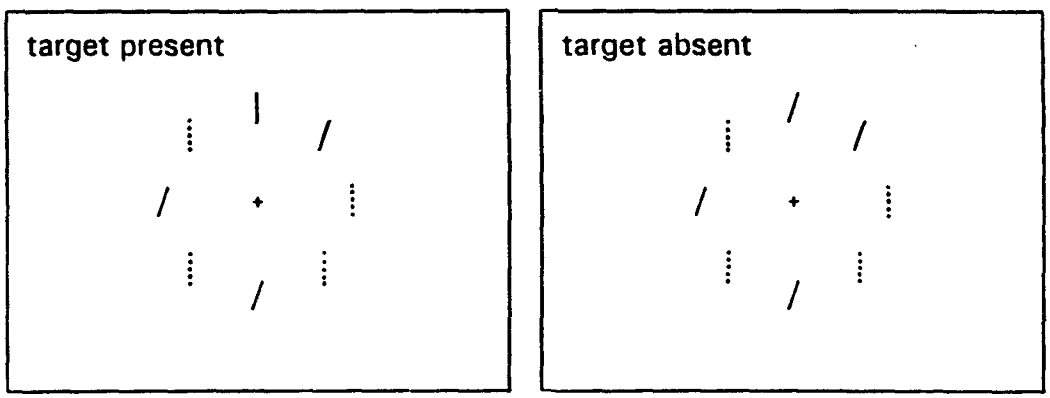

Fig. 1 Examples of stimulus displays used in Experiment 1, both with a target present (left panel) and absent (right panel). Red line segments are solid, green ones dashed.

Color specifications

The fixation point was presented in white (CIE xy-chromaticity coordinates of .286/.307, respectively, and a luminance of 25.2 cd/m^2). The target and the tilted distractors were presented in dim red (.626/.357, 5.3 cd/m^2) and the vertical distractors in bright green (.308/.600; 11.4 cd/m^2). The background was dark grey (.293/.296; 0.7 cd/m^2). All color characteristics were measured with a Photoresearch PR-703A spectrophotometer.

Procedure

A block of trials consisted of 4 (1, 2, 4 or 6 red items) × 4 (1, 2, 4 or 6 green items) × 2 (target present or target absent) × 10 (replicas) = 320 trials. Each subject received four blocks of stimuli, that is a total of 1280 experimental trials. Before the first experimental block subjects received two practice blocks (each consisting of 320 trials, with feedback about the percentage of errors and mean RT after every 40 trials). There was a 10 minutes break between these blocks. Subsequently, each subject was presented with four experimental blocks, with a 20 minutes break after two blocks. Subjects were provided with the opportunity for a break after every 80 trials, when subjects received feedback about their performance (percentage of errors and mean reaction time) on the preceding trials. Subjects were instructed to respond as fast as possible, without making too many errors. Each block took approximately 10 minutes.

All trials started with the presentation of a fixation dot. After 700 ms the stimulus field appeared for 150 ms, an exposure duration too short to make directed eye-movements. If no response was given after 2000 ms or if the response was incorrect, subjects were informed by means of a warning beep that they had committed an error. It was emphasized that subjects should not move their eyes during the course of a trial. It was stressed that a steady fixation would reduce RT and make the task easier.

Before each session (two training blocks or four experimental blocks) subjects were instructed to limit their search to only the red items. It was explained that this strategy would speed up their search.

2.2 Results

Response times longer than 1,000 ms were not included in the analyses. This led to a loss of 0.94% of the trials.

In Fig. 2 mean RTs and error percentages are plotted against the number of displayed red elements (Panel A), separately for target present and target absent trials. The same data are also plotted against the number of green elements (Panel B).

In Fig. 3 mean RTs and error percentages are plotted against the number of displayed green elements, separately for each number of red elements, both for target present (Panel A) and target absent trials (Panel B).

Target present and target absent trials were submitted to separate ANOVAs, with the number of reds (1, 2, 4 and 6) and the number of greens (1, 2, 4 and 6) as main factors.

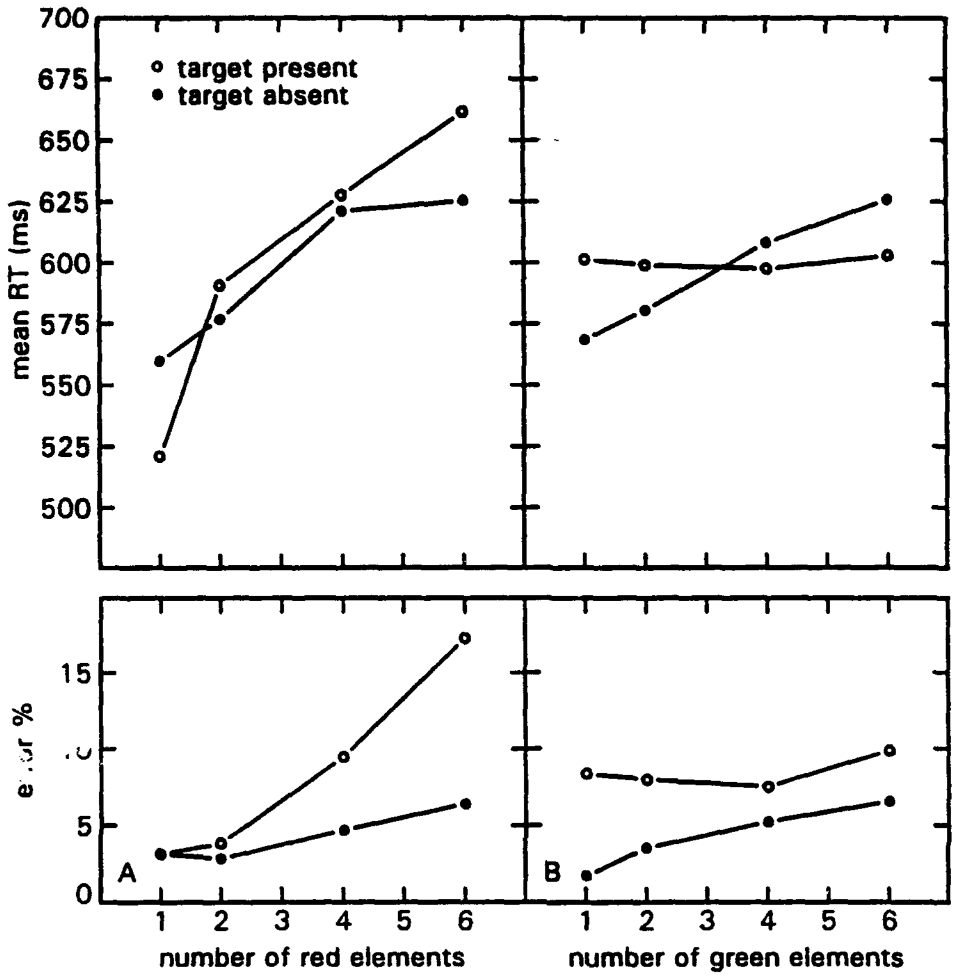

Fig. 2 Mean RTs and error percentages for target present and target absent trials, as a function of the number of red elements (Panel A) and of the number of green elements (Panel B).

For target present trials, there was a significant main effect on RT of the number of red elements [$F(3,21) = 127.0$, $p < 0.01$], but not of the number of green elements. The interaction between the numbers of red and green elements was also not significant. RTs increase with the number of red elements, and not with the number of green ones.

For target absent trials, there was a significant main effect of the number of red items [$F(3,21 = 19.4$, $p < 0.01$] and of the number of green items [$F(3,21) = 57.6$, $p < 0.01$]. The interaction between the numbers of red and green elements was also significant [$F(9,63) = 9.3$, $p < 0.01$]. RTs increase both with the number of red and with the number of green elements. The effect of the number of elements of each color increases with the number of elements in the other color.

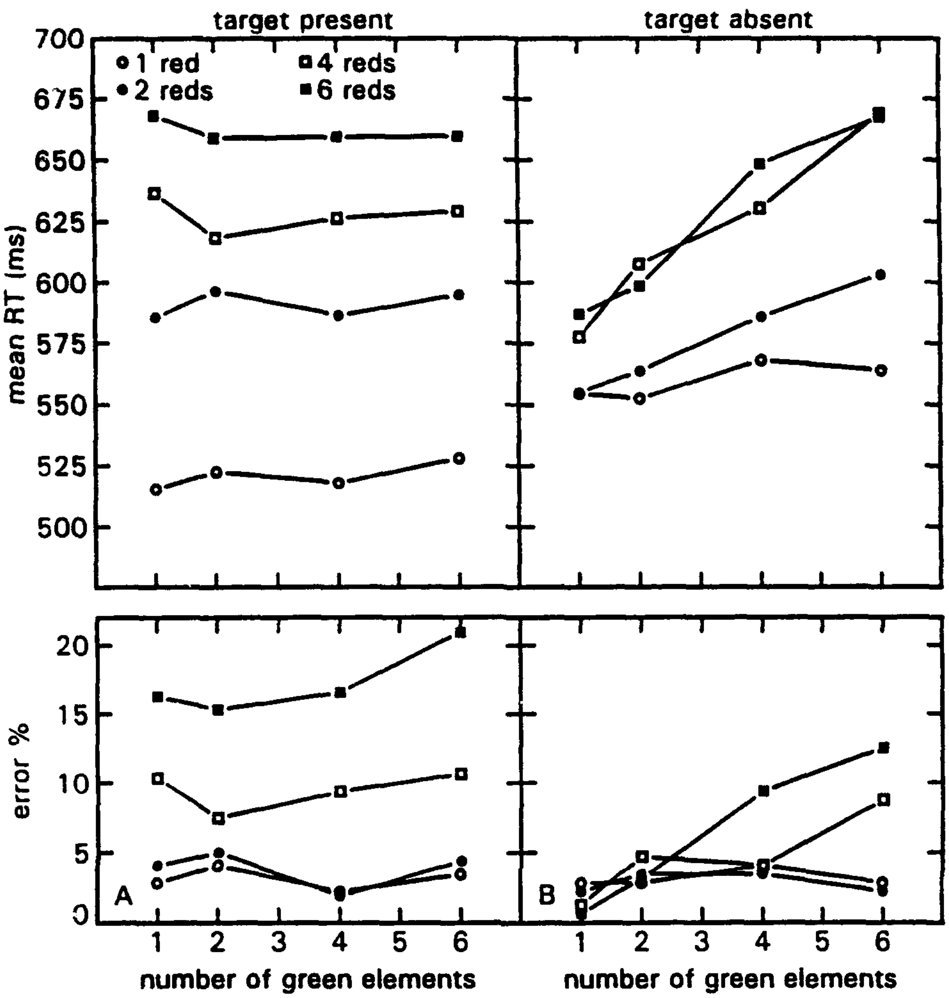

Fig. 3 Mean RTs and error percentages as a function of the number of green elements, separately for each number of red elements, for both target present (Panel A) and target absent trials (Panel B).

In Fig. 4 the data of Fig. 3 are represented in an alternative way. Mean RTs and error percentages are plotted against the number of red elements, separately for each number of green elements, both for target present (Panel A) and target absent trials (Panel B).

To determine the slopes of the RT functions presented in Figs 2, 3 and 4, linear regression analyses were performed on the mean RTs per subject. The mean slopes and intercepts are shown in Table I. T-tests were performed to test whether the slopes were significantly different from zero. The results of these tests are shown in Table I as well. For target present trials, all slopes of RTs as a function the number of red elements differ significantly from zero, whereas all slopes of RTs as a function of the number of green elements do not.

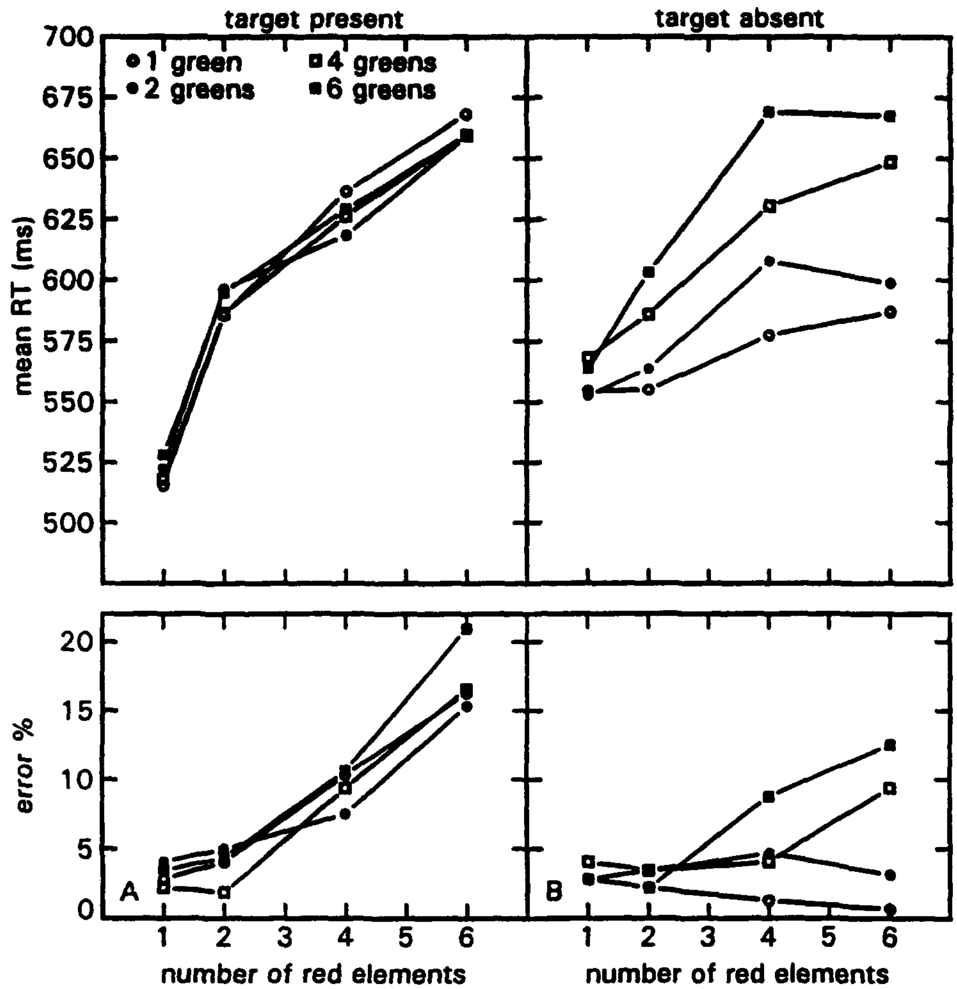

Fig. 4 Mean RTs and error percentages as a function of the number of red elements, separately for each number of green elements, for both target present (Panel A) and target absent trials (Panel B).

To achieve homogeneity of the error rate variance, the mean error rates per cell (i.e., per combination of subject, trial type, number of red elements and number of green elements), were transformed by means of an arcsine transformation before the error rates were submitted to the ANOVAs.

Target absent and target present trials were submitted to separate ANOVAs, with number of reds (1, 2, 4 and 6) and number of greens (1, 2, 4 and 6) as main factors. For target present trials there was a significant main effect on error rate of the number of red elements [$F(3,21) = 50.4$, $p < 0.01$], but not of the number of green elements. The interaction between the numbers of red and green elements was also not significant. The error rate increased with the number of red elements and not with the number of green elements.

Table I Slopes corresponding to the RT functions in Figs 2 to 4.

	intercept [ms]	slope [ms/element]	*t*-value	*p* <
RT as a function of # green elements (see Fig. 2)				
target present	591.0	0.6	1.143	n.s.
target absent	541.5	13.6	8.551	0.01
RT as a function of # red elements (see Fig. 2)				
target present	511.3	25.2	11.424	0.01
target absent	541.6	13.5	4.692	0.01
RT as a function of # green elements, separately for each # reds (see Fig. 3)				
target present				
1 red element	517.2	-0.4	0.336	n.s.
2 red elements	581.9	-0.8	0.559	n.s.
4 red elements	619.4	0.2	0.998	n.s.
6 red elements	647.5	3.1	1.400	n.s.
target absent				
1 red element	545.1	2.3	1.358	n.s.
2 red elements	527.0	12.0	9.377	0.01
4 red elements	540.5	20.4	7.771	0.01
6 red elements	556.8	18.5	6.450	0.01
RT as a function of # red elements, separately for each # greens (see Fig. 4)				
target present				
1 green element	508.8	25.7	9.132	0.01
2 green elements	511.6	24.8	10.985	0.01
4 green elements	508.9	25.2	9.727	0.01
6 green elements	500.4	29.5	11.735	0.01
target absent				
1 green element	535.9	5.3	1.908	0.05
2 green elements	532.1	11.3	3.278	0.01
4 green elements	545.2	17.0	5.917	0.01
6 green elements	553.2	20.6	5.385	0.01

For target absent trials there were main effects on error rate both of the number of red elements [$F(3,21) = 11.2$, $p < 0.01$] and of the number of green elements [$F(3,21) = 9.0$, $p < 0.01$]. The interaction between the numbers of red and green elements was significant as well [$F(9,63) = 3.5$, $p < 0.01$]. The error rate increased with both the number of red elements and the number of green elements. The effect of the number of elements in each color increased with the number of elements in the other color.

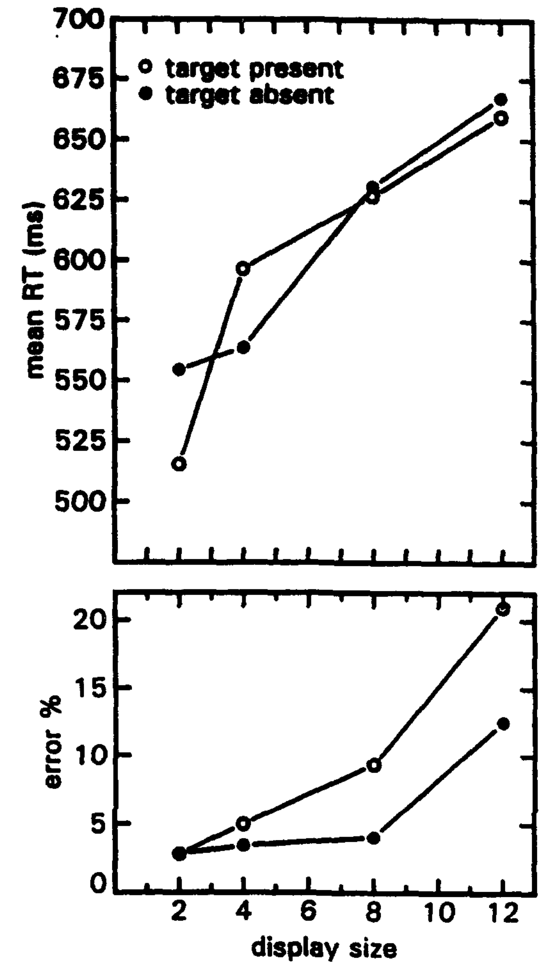

Fig. 5 Mean RTs and error percentages of trials with an equal number of red and green elements, as a function of the display size, both for target present and for target absent trials.

Since all effects on error rate mimic effects on RTs in size, direction and significance, no effects on RTs can be attributed to speed-accuracy trade-offs.

In traditional conjunction search experiments, there is always an equal number of different distractor types. In order to compare the present data with the results of these conjunction search experiments, mean RTs and errors were calculated for those conditions in which there was an equal number of elements of both distractor types. Fig. 5 gives these results. To determine the slopes of both the target present and the target absent RT functions, the individual mean RTs were submitted to linear regression analyses, yielding the regression lines of RT on the total number of displayed elements. Both slopes were significantly greater than zero. For the target present function the intercept was 504.1 ms, and the slope was 14.3 ms/element (t = 4.162, $p < 0.01$); for the target absent function the intercept was 518.7 ms, and the slope was 12.3 ms/element (t = 1.991, $p < 0.05$). RTs increase with display size, with comparable slopes for target present and target absent trials.

In summary, for target present trials, RTs increase with the number of reds, but not with the number of greens. For target absent trials, RTs increase both with the number of reds and with the number of greens.

2.3 Discussion

For target present trials, the results of the present experiment confirm the findings of Egeth et al. (1984). The present findings show that, when searching for a red vertical line segment, search times for target present trials only depend on the number of red elements and not on the number of green ones. Although Egeth et al.'s results can be explained in terms of search for the most salient elements, the present results cannot. Moreover, the present results extend Egeth et al.'s findings to a paradigm using short exposure durations and conjunctions of color and orientation as stimuli, while differences in retinal acuity are controlled for. The target present results are in line with models that suggest a selective search among the displayed red elements. Suggestions by Cave and Wolfe (1990) and Theeuwes (1993), that the results of Egeth et al. (1984) reflect search for the most salient element, are not supported by the present results.

There is, however, a clear difference between the results of the present experiment and the results of Egeth et al. (1984) for target absent trials. While Egeth et al. reported that RT as a function of the number of elements in the distractor color yielded flat search functions for target absent trials as well, in the present experiment search latencies for target absent trials increase with the number of green elements. Also, contrary to the results of Egeth et al., target absent slopes of RTs as a function of the number of red elements are more shallow than the target present slopes. Similar findings have been reported by Humphreys, Quinlan & Riddoch (1989; Müller, Humphreys, Quinlan & Riddoch, 1988), who suggest that grouping effects are at the basis of this type of fast absent responses.

It is interesting to note that the data of displays with equal numbers of red and green elements presented in Fig. 5 are very much like the findings of Treisman (1991), obtained with a similar task. Treisman found slopes of 13.5 and 14.1 ms/element (in Experiments 1 and 2, respectively), whereas error percentages and intercepts are also comparable to the present results. These search slopes have typically been interpreted as evidence for a serial search through all display elements. The present experiment, however, clearly indicates that subjects only search through the red elements. Therefore, it is highly likely that with equal numbers of elements as in a typical visual search task, subjects also search through only a particular subset of elements and not through all elements as is generally assumed.

3 EXPERIMENT 2

Although it is clear that saliency effects cannot account for the results of Experiment 1, it remains unclear which stimulus dimension is used to segregate the candidate target elements from the other ones. Because in Experiment 1 the red elements were less luminant than the green ones, segregation might have been based on color, on luminance, or on a combination of both. Because luminance has shown to be an important variable in visual search tasks (see, e.g., Nagy, Sanchez & Hughes, 1990; Nagy & Sanchez, 1992; Pashler & Badgio, 1985; Egeth & Dagenbach, 1991), it is even likely that luminance (and not color) has guided search.

Experiment 2 was performed to investigate whether selective search among a subset of elements can be based on color proper. Elements in each color are either projected dimly or brightly, so that luminance was no longer a reliable cue for selection anymore. If Experiment 2 replicates the results of Experiment 1 then it is conclusively shown, that the obtained selective search can be purely color-based. If another pattern of results is found, then luminance differences are always necessary to evoke subset-selective search.

In Experiment 2, the red stimuli were presented either dimly or brightly and the green stimuli were presented either dimly or brightly, resulting in four possible luminance conditions (red bright, green bright; red bright, green dim; red dim, green bright; red dim, green dim). In both colors either 1, 2 or 6 elements were presented. The displays with four elements of either color are left out, in order to limit the number of presentations to about the same number as in Experiment 1.

As outlined above, if the results as in Experiment 1 are obtained again, irrespective of the luminance condition, color is proven to be sufficient to guide search selectivity. If not, luminance may be of importance and the issue deserves further investigation.

3.1 Method

Subjects

Eight subjects, ranging in age from 20 to 35 years participated as paid volunteers.

Apparatus

The apparatus was similar to that in Experiment 1.

Task and stimuli

The task was the same as in Experiment 1. The stimuli were somewhat different. Either 1, 2 or 6 elements were presented. Additionally, each combination of numbers of stimuli was presented in four luminance conditions: all red and all green elements are either presented dimly or brightly.

Color specifications

The fixation point was presented in white (CIE xy-chromaticity coordinates of, respectively, .277/.310 and a luminance of 49.2 cd/m^2). The target and the distractors were presented in dim or bright red (.551/.342; 4.4 or 9.7 cd/m^2) and green (.294/.541; 4.4 or 9.7 cd/m^2), with a dark grey background (0.3 cd/m^2).

Procedure

The procedure was the same as in Experiment 1. A block consisted of 3 (1, 2 or 6 red items) × 3 (1, 2 or 6 green items) × 2 (target present or target absent) × 2 (dim or bright red elements) × 2 (dim or bright green elements) × 13 (replicas) = 936 trials. Each subject received two blocks of stimuli, that is a total of 1872 trials. Before the first experimental block, subjects received one practice block, consisting of 936 trials, with feedback after every 40 trials. Between the two experimental blocks, subjects were provided with a 30 minute break. After every 80 trials subjects received feedback and were provided with the opportunity for a break. Stimulus presentation occurred like in Experiment 1. Subjects were not informed about the differences in luminance.

3.2 Results

Trials with response latencies longer than 1,000 ms were not included in the analyses, which led to a loss of 1.54% of the trials.

The results for target present and target absent trials were submitted to separate ANOVAs, with the number of reds (1, 2 and 6), the number of greens (1, 2 and 6), the luminance of red (dim and bright) and the luminance of green (dim and bright) as main factors.

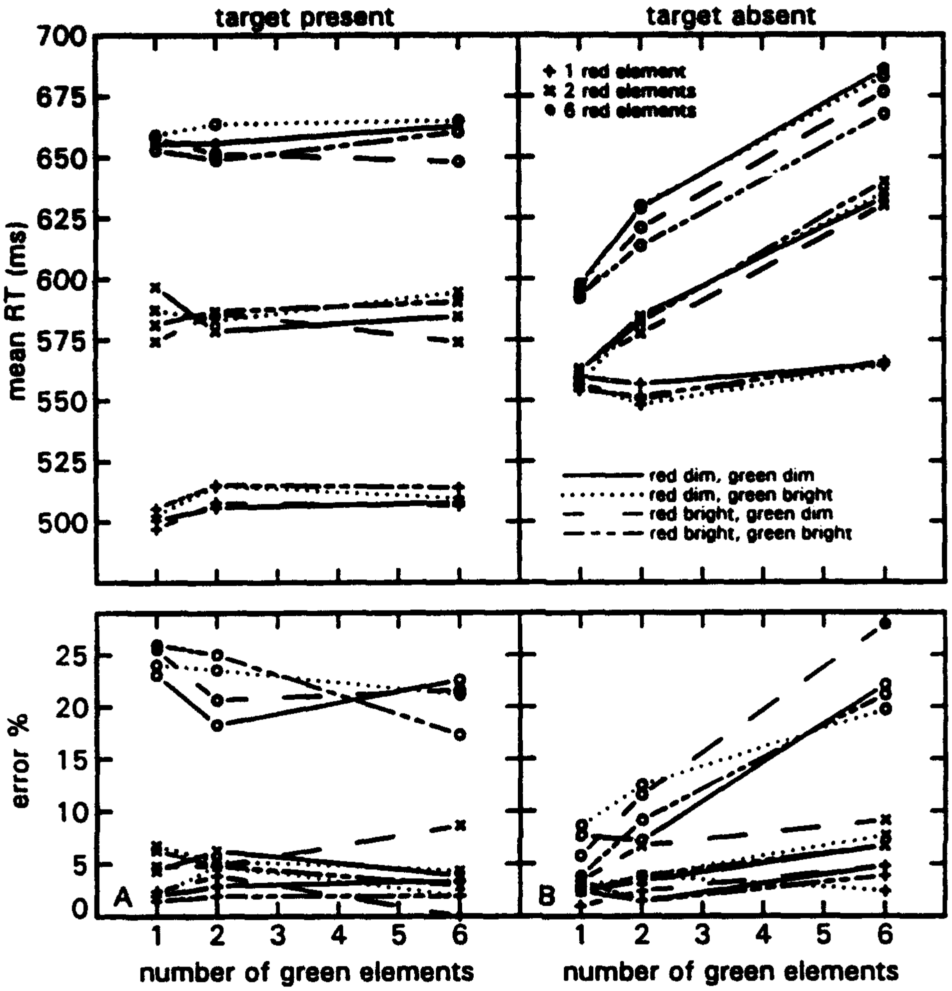

Fig. 6 Mean RTs and error percentages for target present (Panel A) and target absent trials (Panel B), as a function of the number of green elements, separately for each combination of number of red elements and luminance condition.

In Fig. 6 mean RTs and error rate are plotted against the number of displayed green elements, separately for each number of red elements and for each luminance condition, both for target present (Panel A) and for target absent (Panel B) trials.

For target present trials there was only a significant main effect on RT of the number of red elements [$F(2,14) = 112.0$, $p < 0.01$], not of the number of green elements. The interaction between the numbers of red and green elements was not significant. The luminance produced no significant effect on RT whatsoever. RTs increased with the number of reds, and not with the number of greens, whatever the luminances of either the red or the green elements.

For target absent trials there was a significant main effect on RT of the number of red elements [$F(2,14) = 27.0$, $p < 0.01$] and of the number of green elements

[$F(2,14) = 43.1$, $p < 0.01$]. The interaction between the numbers of red and green elements was also significant [$F(4,28) = 28.3$, $p < 0.01$]. The luminances had no effect at all. RTs increased with both the number of red elements and the number of green elements. The effect on RT of each color increased with the number of elements in the other color.

In Fig. 7 the same mean RTs and percentages of errors are plotted against the number of red elements, separately for each number of green elements and for each luminance condition, both for target present (Panel A) and for target absent trials (Panel B).

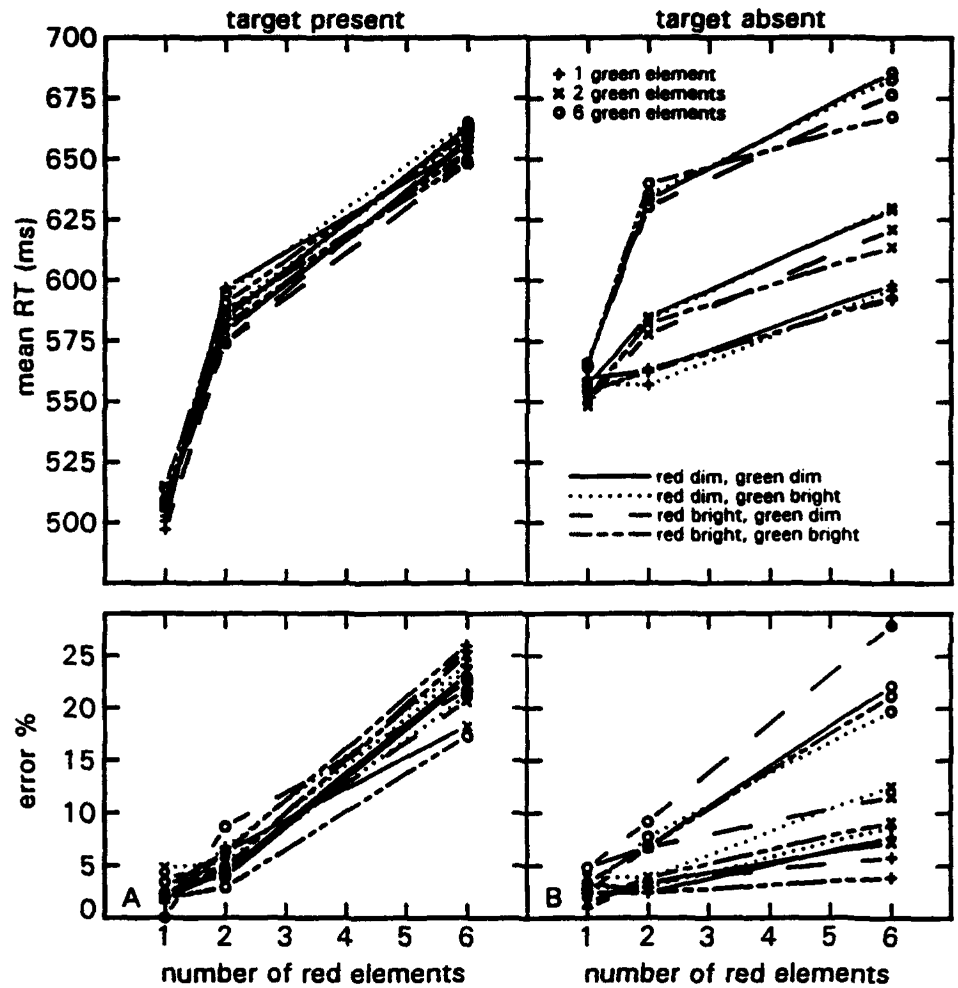

Fig. 7 Mean RTs and error percentages for target present (Panel A) and target absent trials (Panel B), as a function of the number of red elements, separately for each combination of number of green elements and luminance condition.

Table II Slopes corresponding to the RT functions in Figs 6 and 7.

	intercept [ms]	slope [ms/element]	t-value	p <		intercept [ms]	slope [ms/element]	t-value	p <
red dim, green dim					**red bright, green dim**				
RT as a function of # green elements, separately for each # reds (see Fig. 6)					RT as a function of # green elements, separately for each # reds (see Fig. 6)				
target present					**target present**				
1 red element	501.3	1.2	1.448	n.s.	1 red element	497.2	1.8	0.949	n.s.
2 red elements	590.7	-1.3	0.523	n.s.	2 red elements	581.1	-0.9	0.807	n.s.
6 red elements	653.4	1.5	0.508	n.s.	6 red elements	657.4	-1.6	0.983	n.s.
target absent					**target absent**				
1 red element	556.4	1.3	0.714	n.s.	1 red element	550.2	2.5	2.111	0.05
2 red elements	552.8	13.6	5.642	0.01	2 red elements	550.5	13.3	4.832	0.01
6 red elements	587.9	16.6	4.923	0.01	6 red elements	581.9	16.0	7.133	0.01
RT as a function of # red elements, separately for each # greens (see Fig. 7)					RT as a function of # red elements, separately for each # greens (see Fig. 7)				
target present					**target present**				
1 red element	505.5	26.3	10.480	0.01	1 red element	489.7	28.9	9.567	0.01
2 red elements	499.3	26.9	9.183	0.01	2 red elements	506.3	25.2	8.158	0.01
6 red elements	502.0	27.7	8.539	0.01	6 red elements	499.7	25.5	7.577	0.01
target absent					**target absent**				
1 red element	549.2	8.1	2.564	0.05	1 red element	549.3	7.1	2.001	0.05
2 red elements	559.3	11.7	3.722	0.01	2 red elements	543.4	13.2	4.387	0.01
6 red elements	564.9	21.0	8.094	0.01	6 red elements	567.1	19.1	6.803	0.01
red dim, green bright					**red bright, green bright**				
RT as a function of # green elements, separately for each # reds (see Fig. 6)					RT as a function of # green elements, separately for each # reds (see Fig. 6)				
target present					**target present**				
1 red element	507.0	0.7	0.705	n.s.	1 red element	502.5	2.2	1.382	n.s.
2 red elements	582.8	1.8	1.285	n.s.	2 red elements	581.6	1.6	0.847	n.s.
6 red elements	659.8	0.9	0.293	n.s.	6 red elements	648.4	1.9	0.768	n.s.
target absent					**target absent**				
1 red element	549.3	2.2	1.240	n.s.	1 red element	549.2	2.7	1.107	n.s.
2 red elements	547.2	14.9	12.754	0.01	2 red elements	548.1	15.4	7.000	0.01
6 red elements	588.0	16.1	7.562	0.01	6 red elements	581.5	14.4	3.731	0.01
RT as a function of # red elements, separately for each # greens (see Fig. 7)					RT as a function of # red elements, separately for each # greens (see Fig. 7)				
target present					**target present**				
1 red element	500.6	27.5	9.921	0.01	1 red element	501.4	26.2	9.800	0.01
2 red elements	506.0	27.0	12.951	0.01	2 red elements	513.2	23.5	5.464	0.01
6 red elements	508.1	27.2	9.407	0.01	6 red elements	503.1	27.3	8.965	0.01
target absent					**target absent**				
1 red element	544.8	8.4	2.957	0.05	1 red element	546.4	7.8	3.604	0.01
2 red elements	542.2	15.0	4.067	0.01	2 red elements	549.2	11.1	6.725	0.01
6 red elements	566.5	20.3	7.206	0.01	6 red elements	574.9	16.5	4.006	0.01

To determine the slopes of the RT functions, the individual mean RTs were submitted to linear regression analyses, yielding the regression lines of RT on the number of elements of the subset that RT is plotted against. The slopes corresponding to the RT functions in Figs 6 and 7 are shown in Table II. T-tests were performed to test whether the slopes differed significantly from zero. The results of these tests are shown in Table II as well. For target present trials, the slopes of RTs as a function of the number of red elements all differ significantly from zero. Slopes of target present RTs as a function of the number of green elements never reach significance.

To achieve homogeneity of the error rate variance, the mean error rates per cell were transformed by means of an arcsine transformation before the error rates were submitted to the ANOVAs.

The error data of target present and target absent trials were submitted to separate ANOVAs, with number of reds (1, 2 and 6) and number of greens (1, 2 and 6), luminance of reds (dim and bright) and luminance of greens (dim and bright) as main factors. For target present trials, there was only a main effect of the number of red elements [$F(2,14) = 44.5$, $p < 0.01$]. The error rate increased with the number of red elements, not with the number of green ones, irrespective of the luminance conditions.

For target absent trials there were significant main effects on error rate of the number of red elements [$F(2,14) = 8.7$, $p < 0.01$] and of the number of green elements [$F(2,14) = 58.1$, $p < 0.01$]. Their interaction was also significant [$F(4,28) = 5.6$, $p < 0.01$], as were the interaction of the luminances of red and green [$F(1,7) = 6.4$, $p < 0.05$], and the interaction of luminance of red and number of greens [$F(2,14) = 4.2$, $p < 0.05$]. The error rate increased with both the number of red and the number of green elements. The effect of the number of elements in each color increased with the number of elements in the other color. Error rates were highest when the luminances of red and green elements differed. The effect of the number of green elements increased with the luminance of the red elements. These last two effects show that the luminance manipulation has been effective.

As the error functions tend to mimic the RT functions (see Figs 6 and 7), the present findings can not be explained as being the result of a speed-accuracy trade-off.

The pattern of results obtained in Experiment 1 is replicated in the present experiment, irrespective of the luminance of red or green elements.

3.3 Discussion

In Experiment 2 color and luminance of distractor types were orthogonally combined. The luminance of an element carried no information on its color. As a consequence, color information could have been used to guide selection, whereas luminance information could not. The results show, that, irrespective of luminance, RTs for target present trials depend on the number of red elements, and not on the number of green ones. Subjects have been able to search among elements in the target color. It can be conclusively stated, that subjects are able to search selectively through a color-defined subset of elements. Luminance information is not necessary for display segregation.

4 EXPERIMENT 3

Although the experiments above clearly show that search can be limited to a color-defined subset of elements, two issues remain unclear.

Firstly, both in Experiment 1 and in Experiment 2 the target always was a red vertical line segment. Therefore, in theory, search selectivity could be dependent on using red as the target color.

Secondly, it is unclear how flexible the selective search can be. The experiments so far used a consistent mapping procedure: elements that were targets in some trials never were nontargets in other trials. In a variable mapping procedure, targets on some trials are used as nontargets in other trials (see, e.g., Schneider & Shiffrin, 1977; Bundesen & Pedersen, 1983; Bravo & Nakayama, 1992). It has often been shown that consistent mapping may yield different results than does varied mapping (e.g., Schneider & Shiffrin, 1977; Strayer & Kramer, 1990). When using consistent mapping, target present RTs are generally fast and relatively independent of set size. The search selectivity obtained in the present experiments may be (partially) due to the use of consistent mapping.

Experiment 3 was performed in order to find out whether the selective search demonstrated in Experiments 1 and 2 depends upon this consistent mapping. On half of the trials subjects had to search for a red vertical target among red tilted and green vertical distractor elements, as in Experiments 1 and 2. On the other half of the trials subjects had to search for a green vertical target among red vertical and green tilted distractor elements. The target that subjects searched for was varied randomly from trial to trial. Subjects were informed on the color of the target they had to search for by means of a patch that was presented just before each trial in the color of the upcoming target.

Experiment 3 was basically equivalent to Experiments 1 and 2. The task still was to find a vertical line segment among same-colored tilted line segments and differently-colored vertical elements. However, the target color was only known just before the onset of the fixation point that precedes each trial.

If subjects can flexibly choose the group of elements that is searched, it was expected that RTs for target present trials increase with the number of elements in the target color, and are independent of the number of elements in the distractor color. If not, i.e., if search selectivity depends on consistent mapping, it was expected that RTs for target present trials increase both with the number of elements in the target color, and with the number of elements in the distractor color.

4.1 **Method**

Subjects

Eight subjects, ranging in age from 19 to 30 years participated as paid volunteers.

Apparatus

The apparatus was similar to that in Experiment 1.

Task and stimuli

The task was the same as in Experiment 1. The stimuli were somewhat different. As in Experiment 2, of each color only either 1, 2 or 6 elements were presented. On half of the target absent trials the display consisted of green vertical and red tilted line segments, on the other half of the target absent trials the display consisted of red vertical and green tilted line segments. The same displays were used on target present trials, except for that one tilted line segment was replaced by a same-colored vertical line segment.

Color specifications

The fixation point was presented in white (CIE xy-chromaticity coordinates of .277/.310, respectively, and a luminance of 49.2 cd/m^2). The target and the distractors were presented in equiluminant red (.627/.358; 9.6 cd/m^2) and green (.306/.598), with a dark grey background (0.3 cd/m^2).

Procedure

The procedure was the same as in Experiment 1. A block consisted of 3 (1, 2 or 6 red items) $\times$ 3 (1, 2 or 6 green items) $\times$ 2 (target present or target absent) $\times$

2 (red target or green target) × 20 (replicas) = 720 trials. Each subject received two blocks of stimuli, that is a total of 1440 trials. Before the first experimental block, subjects received one practice block, consisting of 720 trials, with feedback after every 40 trials. Between the two experimental blocks subjects had a 30 minute resting period. After every 80 trials subjects received feedback and were provided with the opportunity for a break.

Each trial started with a 700 ms presentation in the center of the screen of a patch in the color of the target that had to be searched for in the directly following stimulus field. Subsequently the fixation point was presented, and then after 700 ms the stimulus array appeared for 150 ms. Like in the previous experiments, if no response was made 2000 ms after the onset of the stimulus array, or if the response was incorrect, subjects were informed that they had committed an error by means of a warning beep. Subjects were told to limit their search to elements in the target color.

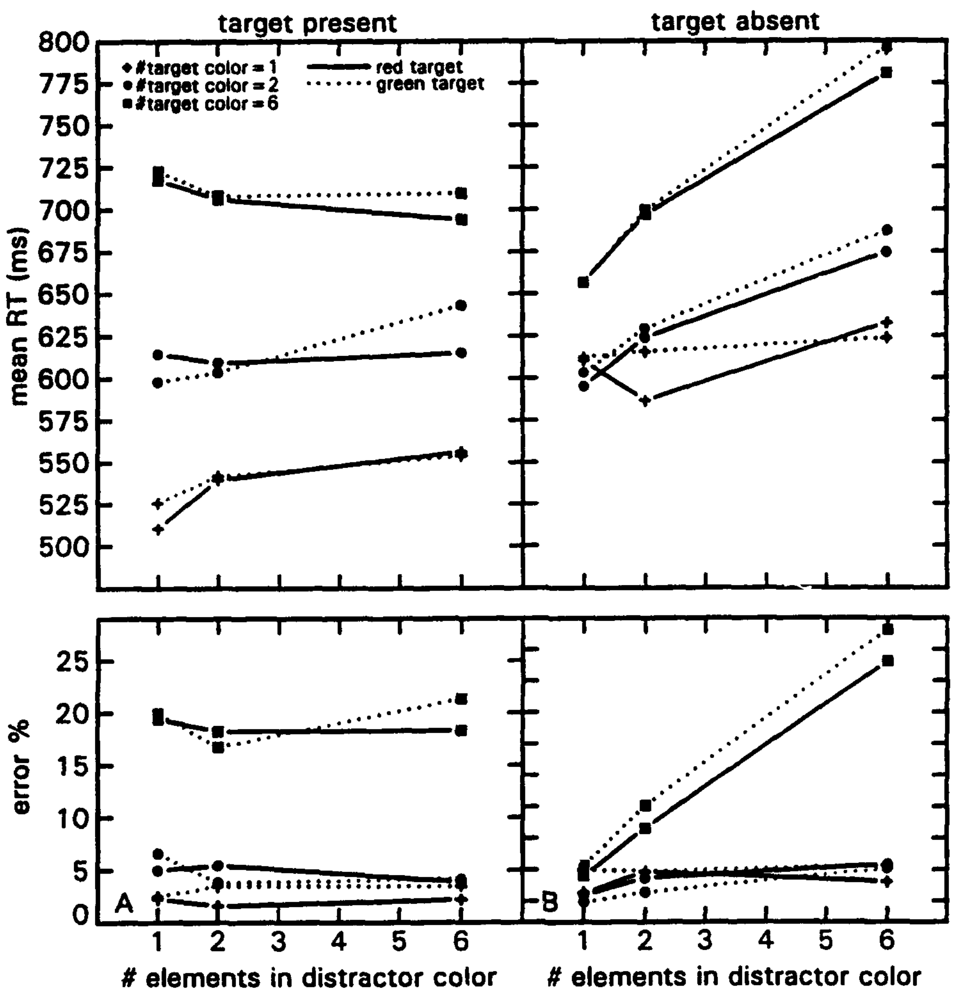

Fig. 8 Mean RTs and error percentages for target present (Panel A) and target absent trials (Panel B), as a function of the number of elements in the distractor color, separately for each number of elements in the target color, for both target colors.

4.2 Results

Trials with response times longer than 1,250 ms were not included in the analyses, resulting in a loss of 1.31% of the trials.

In Fig. 8 RTs and error percentages are plotted against the number of displayed elements in the distractor color, separately for each number of elements in the target color, separately for both target colors. In Fig. 9 the same data are plotted in reverse, yielding RTs and error percentages against the number of displayed elements in the target color, separately for each number of elements in the distractor color, separately for both target colors.

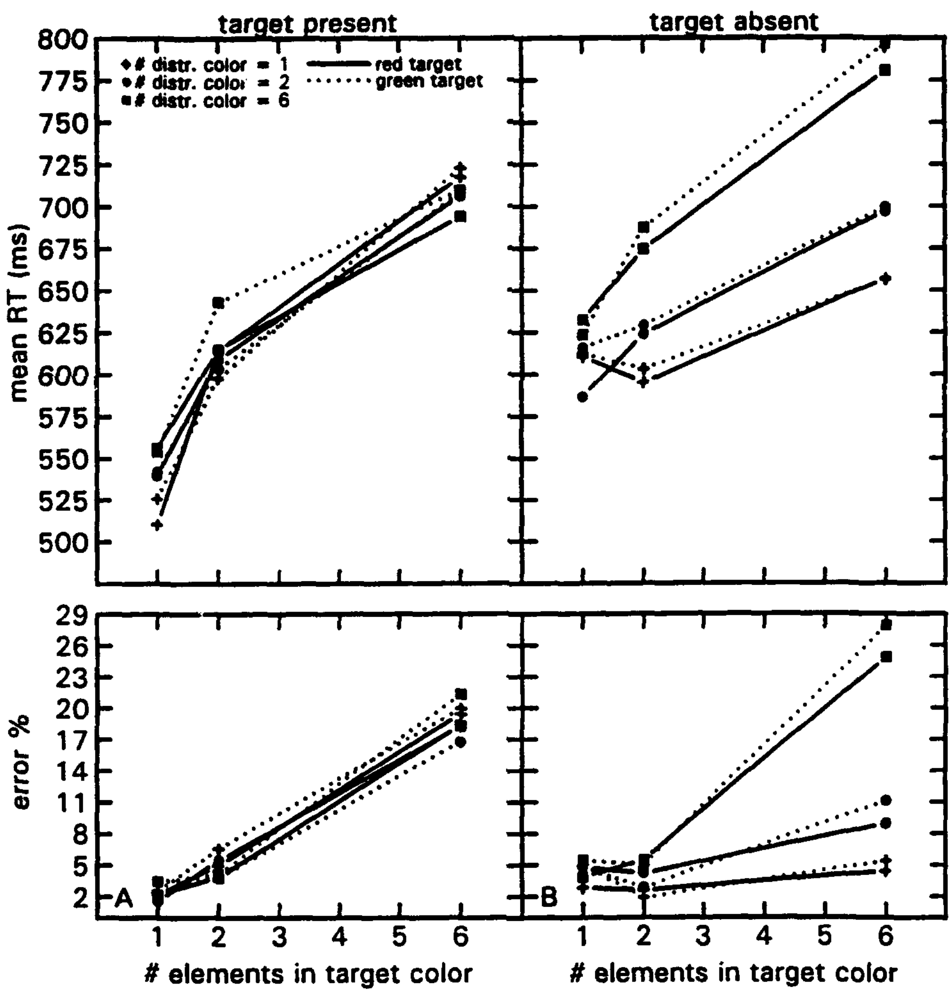

Fig. 9 Mean RTs and error percentages for target present (Panel A) and target absent trials (Panel B), as a function of the number of elements in the target color, separately for each number of elements in the distractor color, for both target colors.

Target present and target absent trials were submitted to separate ANOVAs, with target color (red and green), number of elements in the target color (1, 2 and 6) and number of elements in the distractor color (1, 2 and 6) as main factors.

For target present trials, there were significant main effects on RT of the number of elements in the target color [$F(2,14) = 114.0$, $p < 0.01$] and of the number of elements in the distractor color [$F(2,14) = 4.0$, $p < 0.05$]. Their interaction effect was significant as well [$F(4,28) = 10.2$, $p < 0.01$]. RTs increased both with the number of elements in the target color and with the number of elements in the distractor color. The effect of the number of elements in each color increased with the number of elements in the other color. There was no effect of the target color.

For target absent trials, there were significant main effects on RT of the number of elements in the target color [$F(2,14) = 29.4$, $p < 0.01$] and of the number of elements in the distractor color [$F(2,14) = 60.2$, $p < 0.01$]. Their interaction effect was significant as well [$F(4,28) = 15.9$, $p < 0.01$]. Again, RTs increased with the number of elements in both the target color and the distractor color, and the effect of the number of elements in each color increased with the number of elements in the other color. There was no effect of the target color.

To determine the slopes of the RT functions, the individual mean RTs were submitted to linear regression analyses, yielding the regression line of RT on the number of elements of the subset that RT is plotted against. The slopes of the RT functions in Figs 8 and 9 are listed in Table III. T-tests were performed to test whether the slopes were significantly different from zero. In line with the significant effect on RT of the number of elements in the distractor color that was obtained in the ANOVA, most of the corresponding search function slopes differ significantly from zero. However, these slopes all are well below 10 ms/element. These findings suggest, that the effect of the number of elements in the distractor color can be ascribed to spurious factors, like the occasional search among elements of the distractor color, due to inattendance or to forgetting of the target color cue.

To achieve homogeneity of the error rate variance, the mean error rates per cell were transformed by means of an arcsine transformation before the error rates were submitted to the ANOVAs.

Target present and target absent trials were submitted to separate ANOVAs, with target color (red and green), number of elements in the target color (1, 2 and 6) and number of elements in the distractor color (1, 2 and 6) as main factors. For target present trials there was only a significant main effect on error rate of the number of elements in the target color [$F(2,14) = 81.8$, $p < 0.01$]. The error rate increased with the number of elements in the target color, and not with the number of elements in the distractor color.

Table III Slopes corresponding to the RT functions in Figs 8 and 9.

	intercept [ms]	slope [ms/element]	*t*-value	*p* <
red target				
RT as a function of # elements in the distractor color, separately for each # elements in the target color (see Fig. 8)				
target present				
1 green element in target color	512.1	7.7	3.683	0.01
2 green elements in target color	611.5	0.5	0.284	n.s.
6 green elements in target color	718.5	-4.2	2.897	0.05
target absent				
1 green element in target color	590.9	6.4	2.842	0.05
2 green elements in target color	586.3	14.9	10.148	0.01
6 green elements in target color	640.5	23.6	5.001	0.01
RT as a function of # elements in the target color, separately for each # elements in the distractor color (see Fig. 9)				
target present				
1 green element in distractor color	503.3	36.9	11.142	0.01
2 green elements in distractor color	526.2	30.7	9.479	0.01
6 green elements in distractor color	545.9	25.3	7.381	0.01
target absent				
1 green element in distractor color	588.0	11.0	4.451	0.01
2 green elements in distractor color	572.8	21.0	6.392	0.01
6 green elements in distractor color	609.6	28.7	5.089	0.01
green target				
RT as a function of # elements in the distractor color, separately for each # elements in the target color (see Fig. 8)				
target present				
1 green element in target color	525.9	4.9	2.839	0.05
2 green elements in target color	587.2	9.2	3.450	0.01
6 green elements in target color	718.9	-1.8	0.575	n.s.
target absent				
1 green element in target color	610.8	2.2	11.088	0.01
2 green elements in target color	591.5	16.1	7.831	0.01
6 green elements in target color	636.6	27.0	7.831	0.01
RT as a function of # elements in the target color, separately for each # elements in the distractor color (see Fig. 9)				
target present				
1 green element in distractor color	504.3	37.1	11.088	0.01
2 green elements in distractor color	524.0	31.4	10.114	0.01
6 green elements in distractor color	554.6	27.0	9.718	0.01
target absent				
1 green element in target color	593.8	10.1	2.942	0.05
2 green elements in target color	597.3	17.0	3.837	0.01
6 green elements in target color	605.0	32.5	5.917	0.01

For target absent trials, there were significant main effects on error rate of the numbers of elements in the target color [$F(2,14) = 16.9$, $p < 0.01$] and of the number of elements in the distractor color [$F(2,14) = 28.5$, $p < 0.01$]. Their interaction effect was significant as well [$F(4,28) = 11.6$, $p < 0.01$]. Error rates increased with both the number of elements in the target color and the number of elements in the distractor color. The effect of the number of elements in each color increased with the number of elements in the other color.

4.3 Discussion

The present results show that subjects are able to limit their search to elements of the target color, even if the subject is informed on the target color only trial by trial. The findings obtained in Experiments 1 and 2 therefore can not be attributed to the consistent mapping procedure that was used.

The results of Experiment 3 can be regarded as converging evidence, that search for a conjunctively defined target can be selectively limited to a color-defined subset of the elements. In addition, the results of Experiment 3 show, that subjects can equally selectively search for a red target among equiluminant green ones, as for a green target among red ones. This finding indicates, that the effects reported in Experiments 1 and 2 are not due to specific characteristics of red as a target color, like its apparent brightness. Perceived brightness of an element cannot be derived directly from its luminance. Red is perceived brighter than equiluminant green (see Walraven, 1985, for a review; see also Judd, 1958; Kinney, 1982), so controlling for luminance is not sufficient to control for brightness differences. As most visual search experiments use equiluminant stimuli, the common assumption seems to be that it is luminance, not brightness, that is the variable of importance. In accordance with this assumption, the present results show no differences between search for red among equiluminant greens and search for greens among equiluminant reds.

5 GENERAL DISCUSSION

In the present experiments the critical findings of Egeth et al. (1984) were replicated. When searching for a target that is defined as a conjunction of color and form, response latencies on target present trials increase with the number of elements in the color of the target, and are independent of the number of elements in the non-target color.

The present experiments differ in several important respects from the experiments of Egeth et al. (1984). Egeth et al. had subjects search for a red O in a field of black Os and red Ns, the stimuli remained on the display until response, the stimuli were presented in imaginary square matrix cell centers and in the critical trial blocks the number of red elements was relatively small and always the same. In the present Experiments 1 and 2, subjects had to search for a red vertical line segment in a field of green vertical and red tilted line segments, the stimuli remained on the display for only 150 ms, the stimuli were presented equispaced on an imaginary circle and within all blocks of stimuli the numbers of red and green elements was varied independently.

Taken the number of differences between both paradigms, it is striking that the target present results of the present experiments are completely in line with the target present findings of Egeth et al. (1984). These very differences ensure that salience cannot have guided selective search in the present experiments, so that it can be concluded that Egeth et al.'s results do not have to be the result of searching the salient elements. Of course, it remains possible that the subjects in Egeth et al.'s study used such a search strategy anyway.

In addition, Experiment 2 shows that the obtained selective search among elements of the target color is indeed based on the color of these elements, and not on their luminance or brightness. Finally, Experiment 3 shows that search selectivity is independent of the particular target color that is used, and that subjects are able to switch target color trial by trial and yet retain almost perfect selectivity.

To account for their findings, Egeth et al. (1984) suggested that subjects are able to restrict their search to a subset of the stimuli in the display. After the elements in the distractor color have been segregated in parallel from the elements in the target color, the elements in the target color are searched serially until the target is found. The present target present results are consistent with this interpretation.

On target absent trials, the present data are different from the findings of Egeth et al. (1984). Egeth et al. found steeper search functions for target absent trials than for target present trials, whereas the present experiments show shallower search functions, when RTs are plotted against the number of elements in the target color. This finding is of importance and deserves further investigation. Using similar display configurations, fast absent data have been found previously (see Humphreys, Quinlan & Riddoch, 1989; Müller, Humphreys, Quinlan & Riddoch, 1988). The failure to obtain the same result with heterogeneous distractors, or with irregular stimulus configurations (Quinlan et al., 1989; Müller et al., 1988), indicates that grouping processes may be involved (see, e.g., Bravo & Blake, 1990; Bacon & Egeth, 1991).

The results appear to indicate that pre-attentive segregation guided subjects towards a particular group of the elements that was searched. However, the exact way in which this segregation is controlled remains unclear. One account is offered by Egeth et al. (1984; see also Van der Heijden, 1992, in press; Bundesen & Pedersen, 1983): Subjects know that they have to detect a red-colored target, and therefore segregate, top-down controlled, red elements from differently colored elements. The elements of the target color then are tagged (see, e.g., Trick & Pylyshyn, 1993) and subsequently searched. However, a different account is feasible. Suppose that, more or less in line with a bottom-up account, the stimulus field is only segregated into two groups, based on their color, without subjects knowing what group of elements is of what color. The only information available is, that within each group all elements are of the same color, and that between-groups colors are different. In the second stage, one group of elements is randomly chosen for analysis. If the selected elements are of the target color, the elements are searched for the target. If not, then the other group of elements is selected for further analysis. The viability of this alternative, however, needs much further investigation.

The present experiments show once again, that original FIT (Feature Integration Theory, Treisman & Gelade, 1980) cannot sufficiently explain conjunction search behavior. Moreover, the present results have some implications for some recent FIT-related models.

The present results appear to contradict Treisman and Sato's (1990) conclusions. Treisman and Sato obtained relatively fast conjunction search (with search function slopes of about 10 ms/element) when features are highly discriminable, and considered both a Segregation Hypothesis and a Feature Inhibition Hypothesis. The Segregation Hypothesis assumes that one set of distractors is selectively inhibited, leaving the other set available for attentional processing. The Feature Inhibition Hypothesis assumes that inhibition can be controlled through more than one feature map, reducing the interference from all distractor locations rather than from a single subset. Treisman and Sato decide in favor of the Feature Inhibition account, mainly because of their finding, that the contributions of different dimensions to the slopes appear to be additive. Treisman and Sato take this finding as an indication that each dimension is separately processed before the target is found, and that each dimension plays an independent role in locating the target or in determining its absence. Treisman & Sato interpret the findings of Egeth et al. (1984) to be the result of a different strategy that is used when the target always is to be found within the smaller subset of the elements. However, the slopes of the functions relating RTs to display size in Experiment 1 (see Fig. 5) are only about 14 ms/element, and yet there is no effect of the number of green elements. In the present Experiment 1 no 'small-subset strategy' can have been used, so the present results may be considered as evidence against the Feature Inhibition Hypothesis and as support for some kind of Segregation Hypothesis. Treisman & Sato's dimensional additivity may be explained by assuming differences in selectivity between subjects or even between trials. If, for instance, when searching for a target that is defined as a conjunction of color and size, half of the data reflect selective search among elements that are of the same color as the target, and the other half of the data reflect selective search among elements of the same size as the target, it is not surprising that both the color dimension and the size dimension have independent contributions to search function slopes. In the present experiments color differences were much more salient than orientation differences, so that differences in selectivity between subjects or between trials were less likely.

In Guided Search (Cave & Wolfe, 1990; Wolfe & Cave, 1990; Wolfe, Cave & Franzel, 1989) it is assumed that first, in parallel, elements are divided into distractors and candidate targets, based on the similarity of each element to the target, measured separately on each dimension. The more an element is like the target, the more likely it is to be selected for further analysis. Also, the more salient an element is, the more likely it is to be selected. To account for the results of Egeth et al. (1984), Cave & Wolfe (1990) suggested that salience of elements in the target color caused them to be always selected first. As in the present study the salience of elements is no longer confounded with color, this explanation cannot be used to account for the present findings. To do so, Guided Search would have to assume that salience is only of importance when it is useful information (since in the present experiments elements in the distractor color sometimes are more salient, whereas no effect of the number of elements in the distractor color is found), and that target color is absolutely dominant over target orientation. Many other conjunction tasks then would yield independent effects of both types of distractors on RTs.

At first sight, the present findings seem to be in line with Duncan & Humphreys' (1989) Similarity Theory. According to Duncan and Humphreys, target-distractor similarity and distractor-distractor similarity are the crucial factors that determine visual search performance. Search difficulty increases with increasing target-distractor similarity and with decreasing distractor-distractor similarity (see Treisman, 1991, for a critical discussion). As in FIT, in Similarity Theory stimulus processing starts with something like 'segmentation'. The stimulus field is coded in terms of basic features like orientation and color, and elements that share a certain feature are linked together. Then, subsequently, elements are assigned weights, according to their similarity to some 'template' of the target. The template used in a particular search is under cognitive control. Although subject to noise effects, the weights determine access to VSTM (Visual Short Term Memory, after Sperling's, 1967, recognition buffer), where elements are further analyzed in order to find the target element. To account for the present results, the template must be 'color x', and only elements whose weight exceeds a certain threshold are analyzed. Elements in another color are not compatible with this template, and never make it into VSTM. However, Similarity Theory does not explain how distractor elements in the target color are distinguished from the target element. For that distinction the template should contain information on the target's orientation, so that non-target color distractor elements share a feature with the template as well, and should be selected for further analysis now and then. The present data do not support this prediction. Note that, if it is assumed that one template is used to guide access to VSTM and a second template for testing a selective element on being the target, Similarity Theory can be adjusted to account for the present results.

None of the theories discussed above can explain the present findings without making additional assumptions. The experiments of Egeth, et al. (1984) contained confounding factors such as the salience or the small number of the elements in the target color. The present study shows, that subjects can search selectively among elements of the target color, irrespective of their number, and irrespective of their salience.

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Search for conjunctively defined target can be selectively limited to a color-defined subset of elements

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15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

When searching for a conjunctively defined target, response latencies usually increase with the number of distractor elements, suggesting serial, self-terminating search through all display elements. However, Egeth, Virzi and Garbart (1984) showed that subjects do not necessarily search all display elements, but can limit their search to a color-defined subset of the elements. The present experiments tested Egeth et al.'s conclusions using an improved paradigm. Subjects searched for a target defined as a conjunction of a color and an orientation. RTs for target present trials increased with the number of elements in that color and were independent of the number of elements in the other color, a finding which replicates Egeth et al.'s results. Experiment 1 showed also that selective search of a color-defined subset did not depend on the saliency of the subset. Experiment 2 showed that selective search can be purely color-based and does not depend on luminance or brightness of the subset. Experiment 3 showed that subjects can flexibly change the subset they are searching for trial by trial. Implications of the present findings for current theories of visual search are discussed.

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